NASA-CASA Project

National Aeronautics and Space Administration - Carnegie Ames Stanford Approach

A Report from the
CASA Drought Assessment and Response Tools (DART)

Impacts of the 2011 Drought on Plant Production in Texas, Oklahoma, and New Mexico

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Summary: ***The CASA (Carnegie-Ames-Stanford) ecosystem model was applied with NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) data to assess the change in plant production across the drought-affected region of Texas, Oklahoma, and New Mexico from 2010 to 2011. Substantial declines in plant production and associated losses of forage and fiber products predominated the region in 2011. The largest decline in annual production rates on a unit area (e.g., acre) basis was estimated for pastures and croplands cover types. CASA-estimated production losses in these areas typically ranged from 1.2 to 2 tons per acre of dry matter in 2011 over approximately 5.7 million acres of pastures and croplands. Additionally, the largest decline in annual production in any single cover class on a regional basis was estimated for shrubland vegetation types, due mainly to the extensive area coverage of this ecosystem in the Southern Plains states.***

Background

Net primary production (NPP) by vegetation provides the chemical energy that drives most biotic processes on Earth. NPP represents much of the organic matter that is consumed by microbes and animals. Climate controls on plant production are an issue of central relevance to society, mainly because of concerns about the extent to which NPP in managed ecosystems can provide human populations with adequate forage and fiber products.

One of the most important impacts of severe drought on a region is the loss of plant production due to extreme heat and moisture stress. Such losses can lead to crop failures, reduction in livestock herds, hardening of soils, and extensive wildfires, all in association with increases in the salinity of coastal wetlands and depletion of groundwater aquifers. Consequently, changes in NPP between a baseline year (with near-normal weather conditions) and years of extreme drought can be a valuable assessment indicator that may be computed starting from the small field scale up to the regional level.

The Southern Plains states (Texas, Oklahoma, and New Mexico) drought of 2011 was unusually extreme, in that most locations received less than 50% of normal rainfall amounts and many locations received nearly zero precipitation over an extended period (Redmond, 2011). Calendar year 2011 was the driest Texas has endured since modern recordkeeping began in 1895. From November 2010 through October 2011, Texas saw 23,835 fires that burned more than 3.8 million acres and destroyed 2,763 homes. Rains in October 2011 brought some relief to the region.

For this report, we have summarized results from the CASA (Carnegie-Ames-Stanford) ecosystem model to assess the change in plant production across the Southern Plains states from 2010 to 2011. Direct input of satellite vegetation index "greenness" data from the NASA MODIS sensor into the simulation model with climate variables was used to estimate spatial variability in monthly NPP at a ground resolution of 8-km (Potter et al., 1993 and 2009). These CASA results were designed to be spatially detailed enough to support drought impact assessments in different vegetation management types, e.g., grasslands, woodlands, forests, wetlands, urban areas. Areas burned by wildfires were identified by the MODIS sensor as well and analyze separately from unburned areas in the results that follow.

Review of Modeling Methods and Validation Studies

Monthly NPP of vegetation was predicted using the relationship between greenness reflectance properties and the fraction of absorption of photosynthetically active radiation (fPAR), assuming that net conversion efficiencies of PAR to plant carbon can be approximated for different ecosystems or are nearly constant across all ecosystems (Nemani and Running, 1989; Sellers et al., 1994; Goetz and Prince, 1998; Running and Nemani, 1998). For this study, we used MODIS collection 5 of the Enhanced Vegetation Index (EVI; Huete, et al., 2002 and 2006) as model inputs for PAR interception, aggregated for regional assessments to an 8-km spatial resolution.

As documented in Potter (1999), the monthly NPP flux, defined as net fixation of CO_2 by vegetation, is computed in NASA-CASA on the basis of light-use efficiency (Monteith, 1972). Monthly production of plant biomass is estimated as a product of time-varying surface solar irradiance, S_r, and EVI (for fPAR) from the MODIS sensor, plus a constant light utilization efficiency term (e_{max}) that is modified by time-varying stress scalar terms for temperature (T) and moisture (W) effects (Equation 1).

$$NPP = S_r \, EVI \; e_{max} \; T \; W \tag{1}$$

The CASA e_{max} term was set uniformly at 0.55 g C MJ^{-1} PAR, a value that derives from calibration of predicted annual NPP to previous field estimates. This model setting has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP (Potter et al., 2003).

Monthly average spatial grids from PRISM (Parameter-elevation Regressions on Independent Slopes Model; Daley et al., 2004) for the years 2010 and 2011 were used for precipitation, average maximum temperature, and average minimum temperature inputs to the CASA model. These 4-km resolution climatologies were derived from U. S. weather stations records interpolated first into 30 arc-second data sets. PRISM is unique in that it incorporates a spatial climate knowledge base that accounts for topographic influences such as rain shadows, temperature inversions, and coastal effects, in the climate mapping process.

The 8-km resolution MODIS vegetation index (VI) data sets used as inputs to Equation 1 were generated by aggregating monthly 0.05^o (~5.6 km) data (MOD13C2 version 005) from the USGS LP DAAC. The VI layer was selected from each MOD13C2 spatial composite file and surface water values are converted to “NoData”. Each monthly layer was then multiplied by 0.0001 to scale the data to the standard MODIS VI value range. This aggregation procedure provided the greatest assurance of high-quality, cloud-free VI inputs to the plant production model.

The T stress scalar in Equation 1 is computed with reference to derivation of optimal temperatures (Topt) for plant production. The Topt setting will vary by latitude and longitude, ranging from just above 0^{o} C in the Arctic to the middle thirties in low latitude deserts. The W stress scalar is estimated from monthly water deficits, based on a comparison of moisture supply (precipitation and stored soil water) to potential evapotranspiration (PET) demand using the method of Thornthwaite (1948).

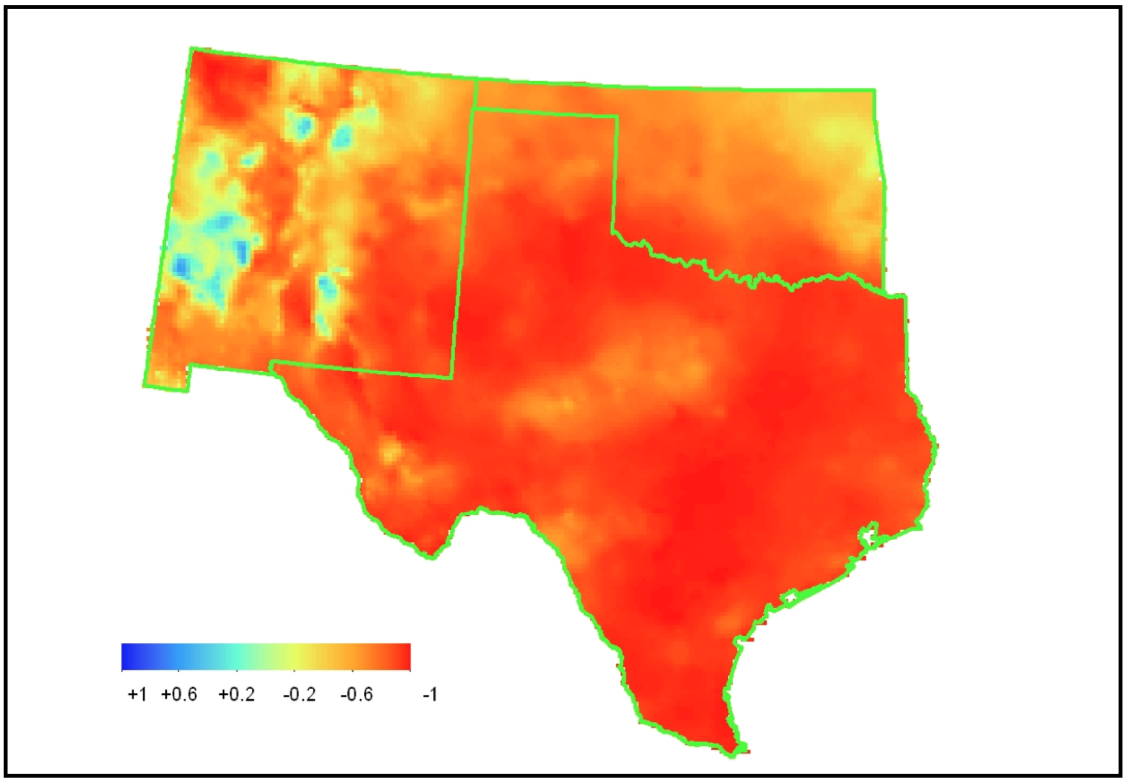
Evapotranspiration is connected to water content in the soil profile layers in the model, according to algorithms described by Potter (1999). The soil model design includes three-layer heat and moisture content computations: surface organic matter, topsoil (0.3 m), and subsoil to rooting depth (1 to 2 m). Maximum rooting depth for cropland and grassland cover types was set at 1 m, whereas forest and shrub cover types were set at 2 m (Potter et al, 2003). These layers can differ in soil texture, moisture holding capacity, and carbon-nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation or volumetric percolation inputs, monthly estimates of PET, and the drainage output for each layer. Inputs from rainfall can recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as seepage and runoff.

Interannual NPP fluxes from the CASA model have been validated previously against multi-year estimates of NPP from tower flux field sites (Behrenfeld et al., 2001; Potter et al., 2012) and tree rings (Malmström et al., 1997). A global comparison of observed NPP (n = 1927) from field based measurements to predicted annual values from the CASA model was made to provide comprehensive validation of terrestrial NPP predictions across all ecosystem types. Observed NPP values were compiled for the Ecosystem Model-Data Intercomparison (EMDI) activity by the Global Primary Productivity Data Initiative (GPPDI) working groups of the International Geosphere Biosphere Program Data and Information System (IGBP-DIS; Olson et al., 1997). Monthly MODIS EVI inputs resulted in a highly significant correlation (R^2 = 0.91) and a close 1:1 match of observed to CASA predicted NPP values.

Drought Impacts in the Southern Plains States

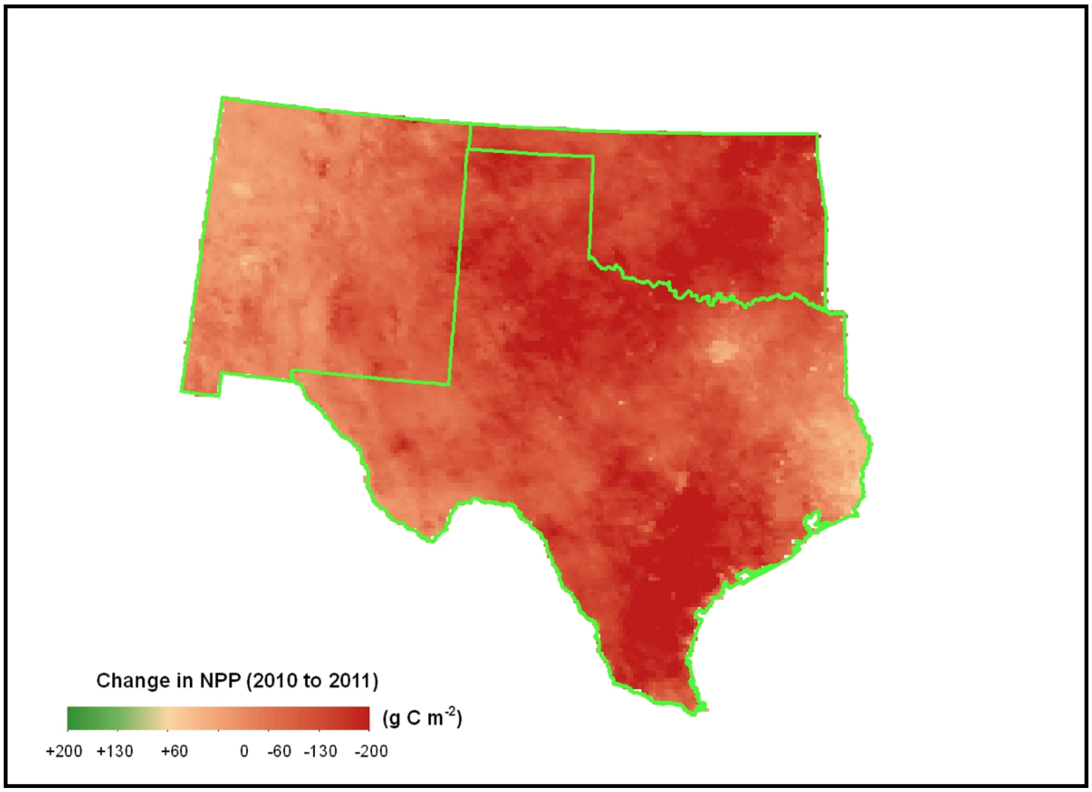
As a monthly indicator of dryness, the Climate Moisture Index (CMI) was first computed as a reference using 2011 PRISM data sets over the region. CMI is an indicator based on rainfall and PET that ranges from -1 to +1, with negative values resulting for relatively dry months/years, and positive values resulting for relatively wet months/years (Willmott and Feddema, 1992). An example of the PRISM-CMI from August 2011 showed extremely low moisture conditions throughout most of Texas, Oklahoma, and southeastern New Mexico. (Figure 1). This dryness pattern nearly identical to that reported by the National Drought Mitigation Center (droughtmonitor archive.html) in late 2011.

Figure 1. PRISM Climate Moisture Index (CMI) for August 2011.



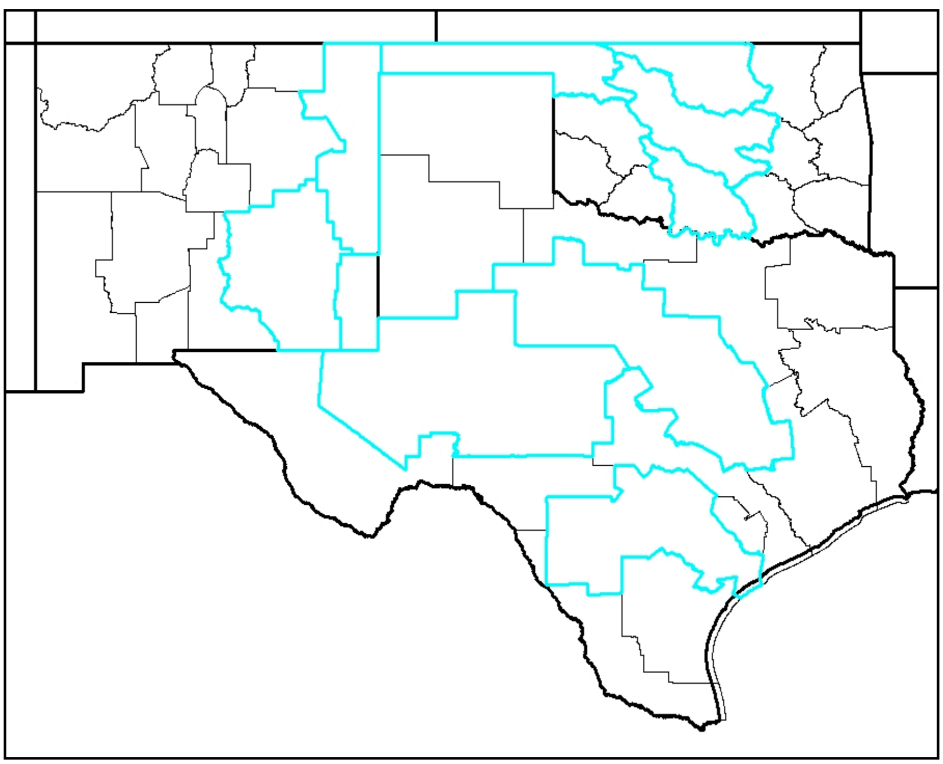
Changes in plant production across the Southern Plains states were calculated as the difference in annual NPP (in grams of carbon per square meter) between 2011 and the baseline year of 2010. CASA predicted that negative values predominated the region with substantial declines in plant production (Figure 2) and associated losses of forage and fiber products. The largest decline in annual production rates on a unit area (e.g., acre) basis was estimated for pastures and croplands cover types (Table 1). CASA-estimated production losses in these areas typically ranged from 1.2 to 2 tons per acre of dry matter over approximately 5.7 million acres of pastures and croplands. Additionally, the largest decline in annual production in any single cover class totaled on a regional basis was estimated for shrubland vegetation types, due mainly to the extensive area coverage of this ecosystem in the Southern Plains states.

Figure 2. Changes in plant production across the Southern Plains states in 2011.



Within states, changes in plant production were next broken down by Regional Water Planning Areas (RWPAs) (Figure 3). Among Texas RWPAs, the largest total losses of plant production were detected in Region F (West Central TX), Brazos G (North Central TX), and South Central TX RWPAs (Table 2). The Coastal Bend RWPA showed the largest declines in annual plant production on a per acre basis. Among Oklahoma Watershed Planning Regions (WPRs), the largest total losses of plant production were detected in the Central, Panhandle, Upper Arkansas, and Lower Washita WPRs (Table 3). The southwestern Beaver-Cache WPR showed the largest declines in annual plant production on a per acre basis. Among New Mexico RWPAs, the largest total losses of plant production were detected in the Lower Pecos Valley and NE New Mexico RWPAs (Table 4). The NE New Mexico RWPA also showed the largest declines in annual plant production on a per acre basis.

Figure 3. Regional Water Planning areas the largest total losses of plant production in 2011 outlined in blue.



Wildfires were detected predominantly in the Texas RWPAs of Region F (West Central TX), Brazos G (North Central TX), Far West TX and the Llano Estacado, whereas in New Mexico and Oklahoma, wildfires were detected predominantly in the RWPAs of Lower Pecos Valley and Middle Rio Grande, and the Middle Arkansas WPR, respectively (Figure 4). The single (non-mixed) vegetation class most impacted by wildfires was shrubland, followed by herbaceous grassland (Table 5).

Figure 4. Areas burned by wildfires in 2011 shown in yellow pixels across the Southern Plains states, as detected by the MODIS satellite.

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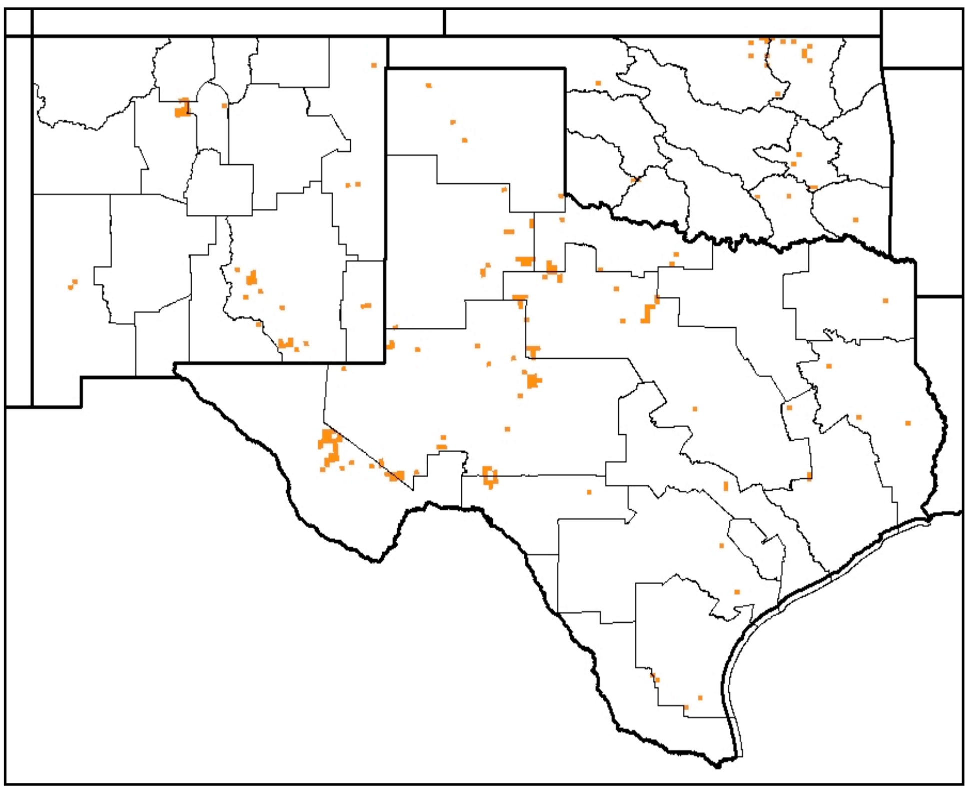

Concluding Remarks

Changes in plant production between a baseline year (with near-normal weather conditions) and years of extreme drought like 2011 can be a valuable assessment indicator for drought impacts. NASA satellite data enables the computation of monthly and annual NPP at the small field scale, up to the regional and state levels, all based on the same imagery and weather data sets. Annual NPP can be readily converted to tons per acre of dry matter (lost or gained), which can be assigned a monetary value in economic assessments of drought impacts. All the required NASA imagery and the weather data inputs to CASA can be used to predict recent (2012) changes in NPP with an approximately latency of just four weeks.

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Table 1. Production Change for NLCD[1] land cover classes in Texas, Oklahoma and New Mexico from 2010 to 2011. Units are grams carbon per sq. meter per year.

Land cover class name	Area cover (km^2)	MIN	MEAN	STD	% of Total Change
Barren Land	1,088	-43.7	-19.6	9.5	0.02
Deciduous Forest	640	-173.3	-156.1	10.1	0.08
Evergreen Forest	23,552	-180.3	-53.4	40.8	0.95
Shrub/Scrub	252,608	-269.7	-88.0	47.4	16.71
Herbaceous	74,112	-240.3	-111.4	42.0	6.20
Hay/Pasture	896	-210.5	-165.2	24.3	0.11
Cultivated Crops	22,080	-255.6	-163.1	32.9	2.71
Woody Wetlands	192	-49.4	-18.6	25.5	0.00
Herbaceous Wetlands	320	-59.8	-12.8	37.7	0.00
Mixed Classes	788,928	-292.4	-123.5	62.3	73.22

Categories were summarized for the minimum (MIN) and average (MEAN) values, and the standard deviation (STD) of the MEAN. The “% of Total Change” was computed as the percentage of the total regional change attributed to individual cover classes, which is function of the Area cover and the MEAN value.

Conversion to tons dry matter per acre was based on the factors of 0.00000197 tons (short) per gram dry matter (per gram carbon) and 4047 sq. meters per acre.

[1] U.S. Geological Survey (USGS) and U.S. Environmental Protection Agency (USEPA) 1999,National Land Cover Data (NLCD), 30-meter resolution aggregated to 8-km, download from http://landcover.usgs.gov/natllandcover.asp

Table 2. Plant Production Change (2010-2011) for Texas Regional Water Planning Areas (RWPA). Units are grams carbon per sq. meter per year.

RWPA	Area cover (km^2)	MIN	MEAN	STD	% of Total Change
Plateau	23,424	-197	-125	28	3.42
South Central Texas	52,672	-262	-177	39	10.85
North East Texas	29,504	-145	-83	28	2.85
Region H	32,192	-195	-94	43	3.53
Lower Colorado	30,272	-249	-153	41	5.41
East Texas	40,448	-132	-20	36	0.94
Coastal Bend	27,712	-292	-209	51	6.76
Region F	101,888	-216	-121	33	14.38
Lavaca	5,504	-234	-179	25	1.15
Rio Grande	28,096	-243	-149	37	4.87
Region C	35,776	-201	-90	45	3.73
Brazos G	80,960	-243	-147	30	13.89
Llano Estacado	51,328	-237	-161	31	9.61
Far West Texas	60,096	-180	-63	28	4.39
Panhandle	53,760	-208	-149	23	9.36
Region B	22,400	-239	-186	18	4.84

Table 3. Plant Production Change (2010-2011) for Oklahoma Watershed Planning Regions. Units are grams carbon per sq. meter per year.

Region Name	Area cover (km^2)	MIN	MEAN	STD	% of Total Change
Beaver-Cache	8,576	-235	-184	22	5.83
Blue-Boggy	9,344	-230	-180	27	6.23
Central	26,304	-235	-173	29	16.89
Eufaula	8,192	-243	-181	31	5.49
Grand	7,488	-210	-169	26	4.70
Lower Arkansas	11,840	-187	-146	18	6.39
Lower Washita	16,128	-229	-175	31	10.48
Middle Arkansas	13,376	-240	-179	22	8.86
Panhandle	24,512	-187	-128	18	11.62
Southeast	11,392	-201	-137	19	5.77
Southwest	10,432	-241	-157	22	6.07
Upper Arkansas	19,008	-231	-165	22	11.65

Categories were summarized for the minimum (MIN) and average (MEAN) values, and the standard deviation (STD) of the MEAN.

Table 4. Plant Production Change (2010-2011) for New Mexico Regional Water Planning Areas (RWPA). Units are grams carbon per sq. meter per year.

RWPA	Area cover (km^2)	MIN	MEAN	STD	% of Total Change
San Juan	24,576	-47.23	-15.88	8.55	2.09
Rio Chama	8,512	-116.62	-40.45	20.82	1.84
Colfax	9,728	-201.31	-86.1	26.25	4.49
Taos	5,888	-87.33	-45.35	17.14	1.43
NW New Mexico	21,056	-49.44	-10.55	13.66	1.19
Jemez y Sangre	5,824	-148.26	-51.76	20.16	1.62
Mora-San Miguel-Guadalupe	24,704	-121.07	-72.22	15.84	9.56
Middle Rio Grande	13,824	-100.73	-32.23	14.3	2.39
Estancia	9,536	-98.62	-60.47	13.55	3.09
SW New Mexico	43,392	-90.24	-37.51	20.3	8.72
Socorro - Sierra	28,480	-114.57	-41.47	20.18	6.33
Lower Pecos Valley	43,712	-162.29	-98.42	19.47	23.05
Tularosa-Sacra.-Salt Basins	17,472	-152.08	-56.35	27.85	5.27
Lea County	11,392	-156.73	-104.92	16.24	6.40
Lower Rio Grande	9,408	-84.92	-42.92	11.98	2.16
NE New Mexico	32,896	-223.04	-115.59	26.82	20.37

Table 5. Percentage of 2011 burned area in NLCD[1] classes for the Southern Plains states.

NLCD Class No.	NLCD Class Name	Percentage
42	Evergreen Forest	4.2
52	Shrub/Scrub	34.2
71	Herbaceous	7.3
99	Mixed Classes	54.4

[1] U.S. Geological Survey (USGS) and U.S. Environmental Protection Agency (USEPA) 1999, National Land Cover Data (NLCD), 30-meter resolution aggregated to 8-km, download from http://landcover.usgs.gov/natllandcover.asp